CHAPTER 3

Limiting Factors

Chapter 3 identifies and prioritizes the key habitat-related physical, chemical, or biological features affecting the viability of ESUs and their component populations in the estuary. These features are referred to as limiting factors. The discussion of limiting factors in this chapter pertains to the estuary and plume; however, upstream limiting factors in some cases have a direct bearing on conditions in the estuary.

Determining Estuary Habitat Limiting Factors

Sources

For this estuary recovery module, limiting factors were identified and prioritized based on a thorough review and synthesis of pertinent literature, supplemented by input from area experts that included staff from NOAA/NMFS's Northwest Fisheries Science Center, NOAA/NMFS – Northwest Regional Office, the Lower Columbia River Estuary Partnership, and the Lower Columbia Fish Recovery Board. Several key documents provided consistent guidance. They included the following:

- *Salmon at River's End: The Role of the Estuary in the Decline and Recovery of Columbia River Salmon* (Bottom et al. 2005)—NOAA technical memorandum
- *Role of the Estuary in the Recovery of Columbia River Basin Salmon and Steelhead: An Evaluation of the Effects of Selected Factors on Salmonid Population Viability* (Fresh et al. 2005)—NOAA technical memorandum
- "Mainstem Lower Columbia River and Columbia River Estuary Subbasin Plan" and its supplement—Northwest Power and Conservation Council (2004)

These three literature sources, and others, identified and prioritized limiting factors in a similar manner. But it should be noted that the three sources have separate goals, and this affects each document's structure and content. Thus, the depth and breadth of information were not always consistent across documents.

Mortality Estimates

Estimates of salmon and steelhead mortality in the estuary and mainstem are not well supported in the literature; however, some modeling efforts have made assumptions about estuary mortality. One example is Ecosystem Diagnosis and Treatment (EDT), a life-cycle model that accounts for the estuarine stage of salmon and steelhead in tributaries of the Columbia River. For lower Columbia River ESUs, EDT assumes 18 to 58 percent mortality for various populations.

In addition, new research is currently under way by NOAA Fisheries, the U.S. Army Corps of Engineers, and Battelle Laboratories to estimate the survival rate of juvenile salmonids in the lower Columbia River. This research involves new technologies for miniaturizing acoustic tags to a size capable of tracking yearling and subyearling juveniles. Current technology developed for the project allows for the tracking of subyearlings of sizes down to approximately 90 mm. Results for the first year (2005) have not been formally released; however, preliminary data indicate an approximate range of survival of 65 to 75 percent for subyearlings and yearlings during their residency in the estuary (Ferguson 2006a). It is probable that actual survival rates are lower than these preliminary estimates suggest because the research did not address mortality among juveniles smaller than 90 mm or mortality occurring in the plume and nearshore.

There are reliable mortality estimates for a few limiting factors. For example, Caspian tern predation is estimated to be responsible for the mortality of about 3.6 to 5.9 million smolts each year (2006 and 1998 data, respectively; from Bonneville Power Administration, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers 2004 and Roby 2006). If these estimates are accurate, tern predation may be responsible for the mortality of up to 6 percent of the outmigrating stream-type juveniles in the Columbia River basin. Good estimates also exist for mortalities caused by double-crested cormorants; these estimates are similar to those for terns.

Other limiting factors, such as pinnipeds, ship wake stranding, and toxic contaminants, have incomplete mortality estimates associated with them. In most other cases it is very difficult to point to a specific limiting factor and then estimate mortality. This is because of the inherent complexity associated with connecting the physical, chemical, and biological features that limit the productivity of salmon and steelhead.

Density-Dependent Mortality

In the Columbia River estuary, limiting factors such as off-channel habitat availability, competition with native and exotic fish, and predation by piscivorous fish and native birds may in part be manifestations of density dependence. Density dependence refers to changes in the size of a population that are themselves a result of the size of the population, such as when a population declines because it has exceeded the amount of resources available to support it. Density-dependent mortality can occur through several mechanisms, such as direct competition for limited food and habitat and changes in the foraging activity of predators. With salmon and steelhead, density-dependent mortality can occur at any stage in the animal's life cycle and may be exacerbated by the introduction of large numbers of hatchery fish released over a relatively short period of time.

How much density-dependent mortality is taking place in the estuary compared to in the ocean is unclear. There is some evidence that density-dependent mortality is occurring in the open ocean. For example, during years when salmon are especially numerous in the ocean, their growth rates are reduced (Peterman 1984 as cited in Ford 2007). One study found that, during years when nearshore ocean productivity was low, survival of wild Snake River chinook decreased as releases of hatchery chinook increased (Levin et al. 2001 as cited in Ford 2007). However, another study found no connection between ocean conditions and density-dependent mortality, which appeared to be occurring among wild Snake River chinook as hatchery steelhead were released (Levin and Williams 2002 as cited in Ford 2007). The authors suggested that the apparent density-dependent mortality could be better explained by interactions in the tributaries or estuary than by interactions in the ocean.

There is growing awareness among scientists studying the Columbia River estuary that mechanisms related to density dependence may limit salmon and steelhead while they are using estuary and plume habitats. Scientists studying Skagit River fall chinook have documented density dependence-related mortality as a result of loss of habitat in the Skagit estuary and believe that such mortality can be attributed to a 75 percent loss of tidal delta estuarine habitat (Beamer et al. 2005). With similar habitat losses in the Columbia River estuary, it is possible that too many fish are competing for limited habitat and associated resources in the estuary at key times, and that the resulting stressors translate into reduced salmonid survival. NOAA/NMFS's Northwest Fisheries Science Center currently is investigating potential density-dependent mortality in the estuary. The *Mainstem Lower Columbia River and Columbia River Estuary Subbasin Plan* raised the specter of density dependence in the estuary and recommended continued research to analyze conditions there (Northwest Power and Conservation Council 2004). Thus, although the occurrence of density dependence-related mortality in the Columbia River estuary has not been proven, given the dramatic changes in habitat opportunity and capacity in the estuary over the last 200 years, it is likely that some of the mortality associated with the limiting factors described in this chapter is related to increased density of juveniles in the estuary.

The estuary recovery plan module assumes that density-dependent mortality that may be occurring in the estuary is manifested in part through limiting factors related to habitat availability, competition, and predation. For this reason, and given the uncertainty about the mechanisms and effects of density dependence in the estuary, density dependence itself is not included as a limiting factor in the module. Neither are the effects of hatchery fish. Although it is likely that hatchery fish influence the estuarine survival of naturally produced fish (possibly through mechanisms of density dependence), the focus of this estuary recovery plan module is the effects of habitat conditions and processes in the estuary and plume, rather than the effects of hatchery or harvest practices. But the degree of density-dependent mortality occurring in the estuary and the role of large releases of hatchery fish in density-dependent mechanisms are worth exploring through further research (see Chapter 6).

Habitat-Related Limiting Factors

Salmonid populations exhibit diverse strategies that guide them through various habitats and ecosystems in specific sequences and patterns. If those sequences and patterns are interrupted, increased mortality may result. Thus, mismatches between the needs of salmonid populations and the availability of habitats to meet those needs can limit salmonid performance in the estuary and plume. The member/vagrant theory discussed in Chapter 2 underscores the need to consider relationships between ESUs' life history strategies and the quality, quantity, and availability of habitats in the estuary and other ecosystems that are interconnected via the salmon and steelhead's complex life cycle.

The habitats that salmonids occupy during their residency in the estuary and plume are formed through the interaction of ocean forces, land, and river flow (Fresh et al. 2005). Flows entering the estuary govern the general availability of habitats, along with sediment transport, salinity gradients, and turbidity, which are themselves aspects of habitat or habitat formation. Over the last 200 years, the magnitude, timing, and frequency of flows have changed significantly, with corresponding effects on the formation and availability of salmonid habitats. Some habitat has been removed, which has reduced the total acreage of the estuary by approximately 20 percent (Fresh et al. 2005). In other cases, particular habitat types have been transformed into other habitat types, and the resulting mosaic of habitats may not be meeting the needs of salmonids as well as the historical pattern of habitats did.

For example, approximately 77 percent of historical tidal swamp has been lost (Northwest Power and Conservation Council 2004), while other shallow-water habitats have increased significantly. The loss of tidal swamps and other forested or vegetated wetlands represents a loss of habitat that ocean-type salmonids use during their estuarine residence. In short, habitat opportunity and capacity have been degraded in the estuary and plume, and alterations in flow have contributed significantly to losses in in-channel, off-channel, and plume habitat.

An important goal of this estuary recovery module is to describe the various habitats and limiting factors that both ocean- and stream-type juvenile salmonids encounter in the Columbia River estuary and plume. However, current scientific understanding of how stream-type juveniles use the various habitats they encounter in the estuary and plume is less robust than what is known about ocean types' habitat use. To fill this important knowledge gap, NOAA/NMFS's Northwest Fisheries Science Center and others are exploring how stream-type juveniles expressing all the different possible life history strategies use individual estuarine habitats.

Affected salmonids: Because of their longer estuary residence times and tendency to use shallow-water habitats, ocean-type ESUs are more affected by flow alterations that structure habitat and/or provide access to wetland or floodplain areas than are stream-type ESUs. Stream types have relatively short estuary residence times and use the plume much more extensively than ocean types do. Thus stream-type salmonids are affected by habitat elements such as the shape, behavior, size, and composition of the plume (Fresh et al. 2005).

Reduced In-Channel Habitat Opportunity

In-channel habitat opportunity in the estuary is a function of the size of river flows, the timing of river flows, incoming and outgoing tides, and the amount and patterns of sediment accretion. Together, tidal action, river flow, and sediment movement create a constantly changing mosaic of channel habitats as water levels rise and fall, sands shift, and salinity gradients move in response to tides. To support salmonids, the various habitats in the estuary need to be connected both spatially and in time. With twice-daily tidal changes, areas that may be accessible at one point during the day may be inaccessible 6 hours later because of tidal fluctuations. Changes in both flow and sediment transport have reduced in-channel habitat opportunity.

Limiting Factor: Flow-Related Estuary Habitat Changes. The ability of juvenile salmon to access and benefit from habitat depends greatly on instream flow (Fresh et al. 2005). Changes in the quantity and seasonality of flows in the estuary have a direct bearing on whether key habitats are available to salmonids, when those habitats are available, and whether and how they connect with other key habitats. In addition, juvenile salmonids have physiological or behavioral traits that set the timing for their transformation to saltwater, and changes in flows may interrupt this timing.

Both the quantity and timing of instream flows entering the Columbia River estuary and plume have changed from historical conditions (Fresh et al. 2005). Jay and Naik (2002) reported a 16 percent reduction of annual mean flow over the past 100 years and a 44 percent reduction in spring freshet flows. Jay and Naik also reported a shift in flow patterns in the Columbia to 14 to 30 days earlier in the year, meaning that spring freshets are occurring earlier in the season. In addition, the interception and use of spring freshets (for irrigation, reservoir storage, etc.) have caused increased flows during other seasons (Fresh et al. 2005). These changes in the volume and timing of Columbia River flow are limiting factors for salmon and steelhead and have affected habitat opportunity and capacity in the estuary and plume.

Limiting Factor: Sediment/Nutrient-Related Estuary Habitat Changes. The transport of sediment is fundamental to habitat-forming processes in the estuary through sediment deposition and erosion (Fresh et al. 2005). An estuary's form is altered primarily through the deposition of sediment—either sediment that is reworked from other parts of the estuary or sediment that enters the estuary from the watersheds or ocean. Sediment moves among each of the components within the estuary, allowing the estuary as a whole to continually be adjusting toward some long-term equilibrium form in response to changes in physical or geomorphic processes (Philip Williams & Associates and Farber 2004). Sediment from the estuary and upstream sources also affects the formation of nearshore ocean habitats north and south of the Columbia River entrance.

Since the late nineteenth century, sediment transport from the interior basin to the Columbia River estuary has decreased about 60 percent and total sediment transport has decreased about 70 percent (Jay and Kukulka 2003). This reduction in the amount of sediment transport in the Columbia River has affected habitat-forming processes in the estuary and plume (Bottom et al. 2005) and is presumed to be a limiting factor for salmon and steelhead. Although the consequences of the reduced transport of sediment through the estuary and plume are not fully understood, the magnitude of change is very large compared to historical benchmarks (Fresh et al. 2005).

Sediment also provides important nutrients that support food production in the estuary and plume. Microdetrital food particles adhere to sediment suspended in the water column, making different food sources available to different species than was the case historically. Currently, organic matter associated with fine sediments supplies the majority of estuarine secondary productivity in the food web (Simenstad et al. 1984 as cited in Northwest Power and Conservation Council 2004).

Reduced Off-Channel Habitat Opportunity

Columbia River access to its historical floodplain is an important factor for rearing ocean-type juvenile salmonids. Historically, flows that topped the river's bank provided juvenile salmonids with access to low-velocity areas in the lower river and estuary that juveniles used as refugia and for rearing; many of these areas were dominated by Sitka spruce tidal swamps, which were an integral component of the estuarine ecosystem. Overbank flows contributed key food web inputs to the ecosystem and influenced wood recruitment, predation, and competition in the estuary (Fresh et al. 2005).

Today, mainstem habitat in the Columbia and Willamette rivers has, in many cases, been reduced to a single channel (Northwest Power and Conservation Council 2004), and channelization of the estuary has eliminated access to an estimated 77 percent of historical tidal swamps (Fresh et al. 2005). In fact, over the past 200 years the surface area of the estuary has decreased by approximately 20 percent (Fresh et al. 2005).

The near elimination of overbank flooding is a function of both reductions in flow volume and increases in the bankfull level of the Columbia River, among other factors.

Figure 3-1 shows diked areas from the estuary mouth to Bonneville dam. This map was generated from a GIS database recently developed by the Lower Columbia River Estuary

Partnership. The new GIS layers provide state-of-the-art statistics and maps depicting the historical floodplain, diked areas, dredged material disposal sites, over-water structures, contaminant monitoring sites, and other key features in the estuary. Some of these features are shown in GIS-based reach maps presented in Appendix A.

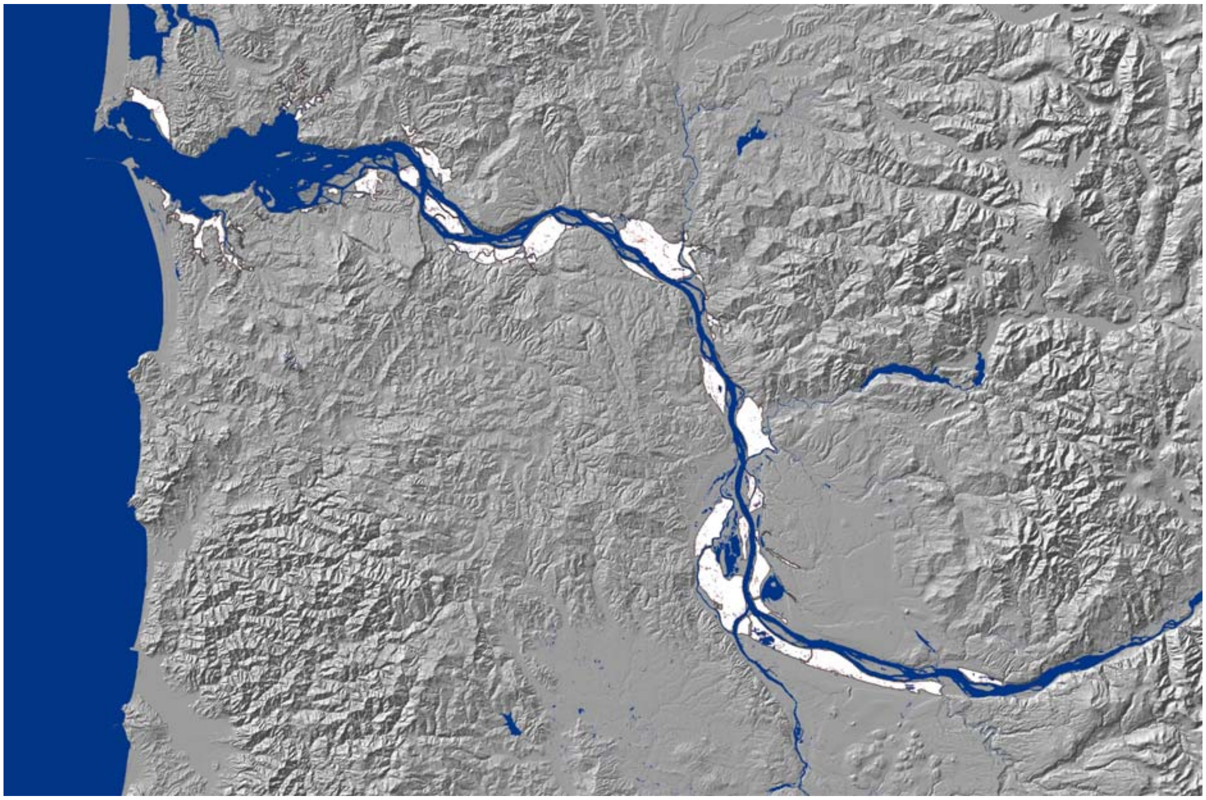

FIGURE 3-1
Diked Areas in the Columbia River Estuary

Limiting Factor: Flow-Related Changes in Access to Off-Channel Habitat. Reduced access to off-channel habitats is a limiting factor for salmon and steelhead because of impacts on food webs and the reduced availability of habitats preferred by fry and fingerlings. Typically, overbank flows were driven by spring freshets, which occurred at the time of year when there was the greatest variety of juvenile salmon and steelhead using the estuary (Fresh et al. 2005). Overbank flows occur much less frequently now than they did historically, in part because climate changes and human alterations have reduced the number of high flows in the Columbia (Jay and Kukulka 2003).

Limiting Factor: Bankfull Elevation Changes. The construction of levees also has reduced the frequency of overbank flows because more river water is needed to cause overbank flow. Historically the bankfull level was 18,000 $m^3 s^{-1}$, while today it is 24,000 $m^3 s^{-1}$—fully one-third more. Only five overbank events have occurred since 1948 (Jay and Kukulka 2003). The reduction in overbank events is a limiting factor because it reduces the availability of food and refugia for ocean-type juveniles rearing in the estuary. Less dominant stream-type juveniles are affected in the same manner.

Reduced Plume Habitat Opportunity

Evidence suggests that the plume supports ocean productivity by increasing primary plant production during the spring freshet period, distributing juvenile salmonids in the coastal environment, concentrating food sources such as zooplankton, and providing refugia from predators in the more turbid, low-salinity plume waters (Fresh et al. 2005). Changes in the volume and timing of Columbia River flow have altered both the size and structure of the plume during the spring and summer months (Northwest Power and Conservation Council 2000).

Limiting Factor: Flow-Related Plume Changes. For juvenile salmonids preparing for ocean life, the plume is believed to function as habitat, as a transitional saltwater area, and as refugia. As mentioned earlier, stream-type ESUs in particular are affected by the size, shape, behavior, and composition of the plume (Fresh et al. 2005).

Over the past 200 years characteristics of the plume have been altered, and conditions caused by reductions in spring freshets and associated sediment transport processes may now be suboptimal for juvenile salmonids (Casillas 1999). Plume attributes affected by changes in flow include surface areas of the plume, the volume of the plume waters, the extent and intensity of frontal features, and the extent and distance offshore of plume waters (Fresh et al. 2005).

Limiting Factor: Sediment/Nutrient-Related Plume Changes. It is believed that the sediment and nutrients transported in the plume fuel ocean productivity and provide relief from predation (Casillas 1999). This is particularly true for stream-type ESUs, who use the plume more extensively than ocean types do and thus are more affected when the amount of plume habitat is reduced.

Limiting Factor: Water Temperature

Water temperatures of between 20° and 24° C are considered the upper range for cold-water species such as salmonids (National Research Council 2004). Alterations in water temperature affect the metabolism, growth rate, and disease resistance of salmonids, as well as the timing of adult migrations, fry emergence, and smoltification (Lower Columbia Fish Recovery Board 2004 as cited in National Marine Fisheries Service 2000).

Since 1938, summer water temperatures at Bonneville Dam have increased 4 degrees on average (Lower Columbia Fish Recovery Board 2004). Among-year variability in temperature has been reduced by 63 percent since 1970 (Lower Columbia Fish Recovery Board 2004). As shown in Figure 3-2, temperatures entering the estuary (as measured at Bonneville Dam) have increased steadily since 1938. Temperatures also exceed 20° C earlier during the year and more frequently than they did historically (National Research Council 2004).

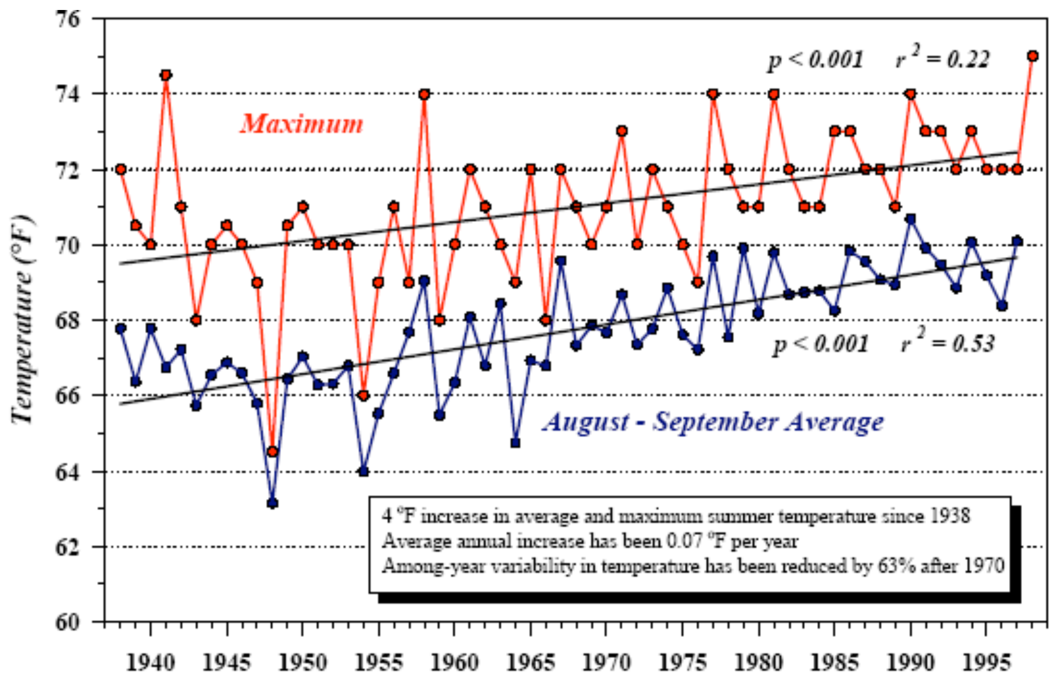

FIGURE 3-2
Temperatures of Water Entering the Estuary
(Reprinted from Lower Columbia Fish Recovery Board 2004.)

Limiting Factor: Stranding

In the estuary, large ships passing through the navigational channel produce bow waves that crash against shorelines in Oregon and Washington. Small ocean-type fry and fingerlings rear within inches of shore and may become stranded as waves intersect the bank and recede (Ackerman 2002), although the extent of this problem is unclear. A 1977 study by the Washington Department of Fisheries (WDF) estimated that more than 150,000 juvenile salmonids—mostly chinook—were stranded at five test sites (Bauersfeld 1977).

A NOAA technical memorandum (Hinton and Emmett 1994) published in 1994 concluded that the problem was not as significant as documented in the WDF report. As part of the channel deepening project being conducted by the U.S. Army Corps of Engineers, a two-part study of stranding was initiated by the University of Washington and the Portland District of the Corps. The study is designed to measure differences in stranding events before and after channel deepening activities. The first study was published in February 2006 (Pearson et al. 2006). In general, the report documents mortality attributed to stranding events for three test sites; it also builds on other recent work to determine the conditions that increase the likelihood of stranding events. No attempt was made to determine an estimate of mortality from this limiting factor for the entire estuary.

Food Web-Related Limiting Factors

Energy released from the Columbia River and the ocean converges in the estuarine, nearshore ocean, and plume environments where, combined with the biological energy of primary plant production, it forms the basis for life in the estuarine ecosystem. Ultimately, energy for the ecosystem begins with sunlight, sunlight leads to plant growth, plants are eaten by animals, and animals eat each other. Energetic processes, then, determine what is being eaten and by whom.

For the past 4,000 years, salmon and other native species have evolved together in response to the basic inputs of energy and their circulation through the ecosystem. The result has been the development of an intricately structured food web in the estuary that encompasses food sources, food availability, and inter- and intra-species relationships. Although stable ecosystems go through cycles of change in energy flows over time, basic energy pathways frequently remain unaltered. As the flow of energy through the ecosystems changes, so do the relationships among species and between species and their habitats. Competition and predation relationships shift and the abundance of species increases or decreases, depending on species' ability to adapt to changing conditions. Changes in any one of the elements of the food web, such as food sources or availability, can ripple throughout the ecosystem and have potentially far-reaching effects on salmonids and other species.

As part of the food web, plant materials known as detritus are consumed by juvenile salmonids, either directly or indirectly through other organisms that feed on the detritus (Northwest Power and Conservation Council 2004). There is evidence that a shift in plant primary production in the estuary—from a macrodetrital to a microdetrital base—has significantly changed the food web and that complex inter- and intra-species relationships have been permanently altered (Northwest Power and Conservation Council 2004). Food web-related conditions that may have reduced the productive capacity of the estuary include reduced foraging habitat, changes in detrital sources, and fine sediment inputs. By disrupting the food web, these conditions have increased competition and predation (Bottom et al. 2005).

Insects also may play a crucial role in maintaining the food web. A recent University of Washington master's thesis demonstrated the importance of midge insects in the diet of juvenile chinook salmon occupying shallow-water habitats in the Columbia River estuary—emerging chironomids were the dominant prey for chinook of all sizes (Lott 2004). The importance of flora that support insect availability in emergent marsh, scrub-shrub wetland, and forested wetlands used by salmonids with ocean-type life history strategies is likely to become an area of greater interest by scientists.

Affected salmonids: Ocean-type ESUs are more likely than stream-type juveniles to be affected by food web alterations because of their use of estuary habitats and their longer residency times. Stream-type ESUs are more influenced in the plume environment because of reduced fine-sediment inputs leaving the estuary.

Food Source Changes

As described below, changes in the detrital sources that form the base of the estuarine food web have been significant and represent a limiting factor for salmonids. Figure 3-3 shows a conceptual model of the estuary food web developed by the U.S. Army Corps of Engineers. The historical tidal marsh macrodetritus-based food web is displayed at the top of Figure 3-3, while the current food web, which is based on imported microdetritus, is shown at the bottom.

Limiting Factor: Reduced Macrodetrital Inputs. The estuarine food web formerly was supported by macrodetrital inputs of plant materials that originated from emergent, forested, and other wetland rearing areas in the estuary (Northwest Power and

Conservation Council 2004). Today, detrital sources from emergent wetlands in the estuary are approximately 84 percent less than they were historically (Bottom et al. 2005).

Macrodetrital plant production has declined as a result of the construction of revetments along the estuary shorelines, the disposal of dredged material in what formerly were shallow or wetland areas where plant materials or insects could drop into the water, and reductions in flow. Flow reductions affect detrital sources by limiting the amount of wetlands—areas that normally would be contributing microdetritus to the food web—and cutting the number of overbank flows. Historically, much of the detrital inputs occurred during overbank events, which provided additional shallow-water habitat for juvenile salmonids and resulted in significant detrital inputs to the estuary. As mentioned earlier, overbank events occur much less frequently today than they did historically.

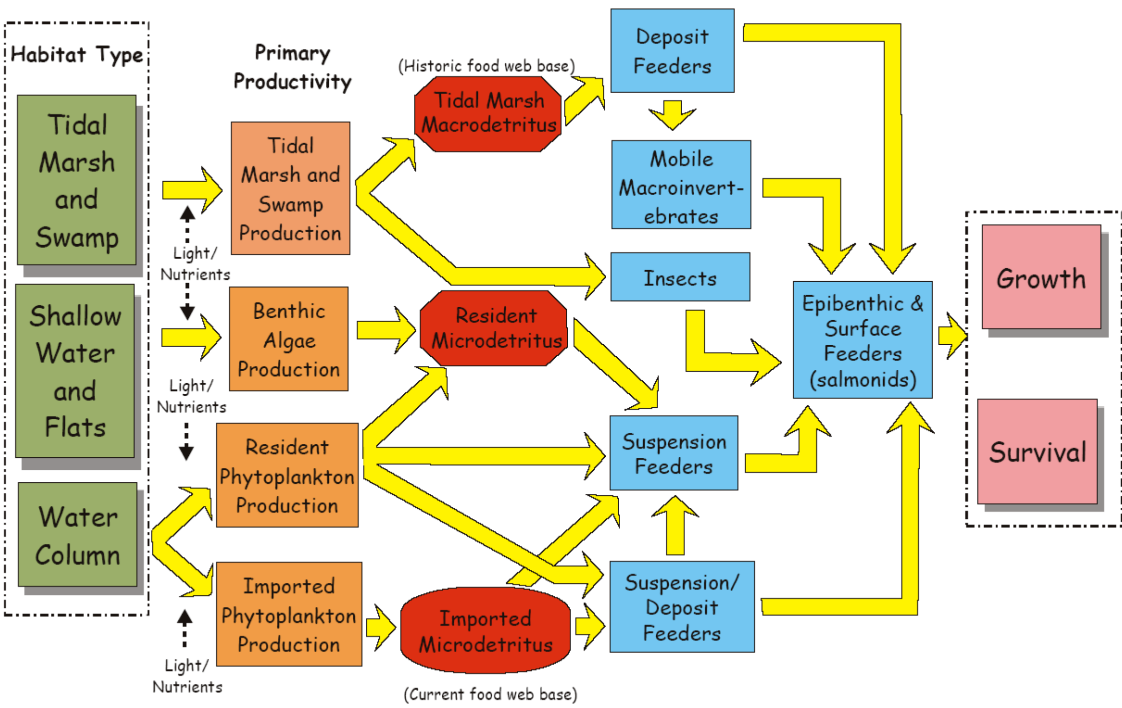

FIGURE 3-3
Conceptual Model of the Columbia River Estuary Food Web

Limiting Factor: Increased Microdetrital Inputs. Instead of being supported by local plant production, the current food web is based on decaying phytoplankton delivered from upstream reservoirs. The amount of this microdetritus has increased dramatically (Bottom et al. 2005). The switch in primary production in the estuary from a macrodetritus-based source to a microdetritus-based source has lowered the productivity of the estuary (Bottom et al. 2005).

The substitution of detrital sources in the estuary also has contributed to changes in the spatial distribution of the food web (Bottom et al. 2005). Historically the macrodetritus-based food web was distributed evenly throughout the estuary, including in the many shallow-water habitats favored by ocean-type salmonids. But the contemporary microdetrital food web is concentrated within the estuarine turbidity maximum in the middle region of the estuary (Bottom et al. 2005). This location is less accessible to ocean-type ESUs that use peripheral habitats and more accessible to species such as American shad that feed in deep-water areas.

Pelagic fish such as shad may also benefit from the fact that the estuarine turbidity maximum traps particles and delays their transport to the ocean up to 4 weeks, compared to normal transport of around 2 days (Northwest Power and Conservation Council 2004). The estuarine turbidity maximum is thought to contain bacteria that attach to detritus. Together these represent the primary food source in the estuary today (Northwest Power and Conservation Council 2004).

Competition and Predation

Predation and competition for habitat and prey resources limit the success of juvenile salmonids entering the estuary and plume. Both spatial and energetic losses can involve either density-dependent or density-independent processes (Bottom et al. 2005). Spatial and temporal losses of habitat and large pulses of hatchery juveniles may, under some conditions, result in density-dependent salmonid mortality (Bottom et al. 2005).

Competition among salmonids and between salmonids and other fish may be occurring in the estuary (Lower Columbia Fish Recovery Board 2004), with the estuary possibly becoming overgrazed when large numbers of ocean-type salmonids enter the area. Food availability may be reduced as a result of the temporal and spatial overlap of juveniles from different locations (Lower Columbia Fish Recovery Board 2004 as cited in Bisbal and McConnaha 1998).

Ecosystem-scale changes in the estuary have altered the relationships between salmonids and other fish, birds, and mammals species, both native and exotic. Some native species' abundance levels have decreased from historical levels—perhaps to the point of extinction—while others have increased to levels far exceeding those in recorded history, with associated changes in predation of salmon and steelhead juveniles.

The presence of non-indigenous fish, invertebrates, and plants in species assemblages indicates major changes in aquatic ecosystems (Northwest Power and Conservation Council 2004). Globally the introduction of such species is increasing, a fact that is attributable to the increased speed and range of world trade, which facilitates the transport and release—whether intentional or not—of non-indigenous species (Northwest Power and Conservation Council 2004). In the estuary, the introduction of exotic species has altered the ecosystem through competition, predation, disease, parasitization, and alterations in the food web.

Non-native species affect ocean-type ESUs more than they do stream-type ESUs because of the ocean types' longer juvenile estuary residency times and use of shallow-water habitats.

Limiting Factor: Native Fish. The northern pikeminnow is a native piscivorous fish that preys on juvenile salmonids in the estuary. Although pikeminnows have always been a significant source of mortality for juvenile salmonids in the Columbia River, changes in physical habitats may have created more favorable conditions for predation (Northwest Power and Conservation Council 2004). These changes include reduced flows and favorable micro-habitats formed by pilings, pile dikes, and other over-water structures. The diet of pikeminnows varies with age, with the largest adults representing the biggest risk to juvenile salmonids. Both ocean-type ESUs and stream-type ESUs are affected, but for different reasons. Ocean-type juveniles are susceptible because of their longer estuary residency times and use of shallow-water habitats. Stream-type juveniles are susceptible because they are leaving faster, deeper water to forage for food in shallow areas that are frequented by pikeminnow.

Limiting Factor: Native Birds. As a result of estuary habitat modifications, the number and/or predation effectiveness of Caspian terns, double-crested cormorants, and a variety of gull species has increased (Fresh et al. 2005). In 1997 it was estimated that avian predators consumed 10 to 30 percent of the total estuarine salmonid smolt production in that year (Northwest Power and Conservation Council 2004). The draft 2005 season summary of *Research, Monitoring, and Evaluation of Avian Predation on Salmonid Smolts in the Lower and Mid-Columbia River* (Collis and Roby 2006) estimates that 3.6 million juvenile salmonids were consumed by terns in 2005. Stream-type juvenile salmonids are most vulnerable to avian predation by Caspian terns because the juveniles use deep-water habitat channels that have relatively low turbidity and are close to island tern habitats. Double-crested cormorants consume a similar number of juvenile salmonids (approximately 3.6 million juveniles) from their East Sand Island nesting grounds (Collis and Roby 2006).

Limiting Factor: Native Pinnipeds. The abundance of native pinnipeds has steadily increased since passage of the Marine Mammal Protection Act in 1972. Harbor seals, Steller sea lions, and California sea lions all prey on salmon and steelhead in the estuary (Northwest Power and Conservation Council 2004). Diet studies indicate that pinnipeds consume both juvenile and adult salmonids. Estimates of adult mortality that occurs at Bonneville Dam because of sea lions ranged from a low of 0.4 percent in 2002 to a high of 3.4 percent in 2006 (Federal Register 2007). These estimates do not account for pinniped mortality occurring downstream of Bonneville Dam. There are no official estimates of downstream mortality on adult spring chinook and winter steelhead (both of which are stream-type salmonids); however, unsubstantiated estimates are as high as 10 percent, which would equate to about 29,000 adult fish.

Limiting Factor: Exotic Fish. At least 37 exotic fish species are now found in the Columbia River estuary (Northwest Power and Conservation Council 2004). American shad were introduced into the Columbia River in the 1880s, and adult returns now exceed 4 million in a single year (Northwest Power and Conservation Council 2004). While shad do not eat salmonids, they exert tremendous pressure on the estuary food web given the sheer weight of their biomass. Other exotic fish in the estuary, such as smallmouth bass, walleye, and catfish, are piscivorous; however, their abundance levels are relatively small.

Limiting Factor: Introduced Invertebrates. Twenty-seven non-native invertebrate species have been observed in the estuary and documented by the Lower Columbia River Aquatic Non-indigenous Species Survey (Sytsma et al. 2004). Recent surveys have documented that the estuarine copepod community has changed from a system dominated by a single introduced species, *Pseduodiaptomis inopinus*, to a system dominated by two newly introduced Asian copepods: *Pseudodiaptomis forbesi* and *Sinoclaanus doerri* (Santen 2004). In some cases, the abundance of non-native invertebrates can alter food webs through their wide distribution and key role in the food chain (Northwest Power and Conservation Council 2004).

Limiting Factor: Exotic Plants. The introduction of non-indigenous plant species also has altered the estuary ecosystem. Exotic plant species often out-compete native plants, which results in altered habitats and food webs (Northwest Power and Conservation Council 2004). About 18 aquatic plants have been introduced into the estuary since the 1880s

(Sytsma et al. 2004). Examples of non-indigenous plant species include purple loosestrife, Eurasian milfoil, parrot feather, and Brazilian elodea. In addition to out-competing native plants, introduced plant species can contribute to poor water quality and create dense, monospecific stands that represent poor habitat for native species (Northwest Power and Conservation Council 2004). In turn, these new plant communities may alter insect and detritus production in and around vegetated wetlands.

Toxic Contaminants

The quality of habitats in the Columbia River estuary is degraded as a result of past and current releases of toxic contaminants (Fresh et al. 2005), from both estuary and upstream sources. Historically, levels of contaminants in the Columbia River were low, except for some metals and naturally occurring substances (Fresh et al. 2005); today, contaminant levels in the estuary are much higher. Currently the estuary receives contaminants from more than 100 point sources and numerous non-point sources, such as surface and stormwater runoff from agricultural and urban sources (Fresh et al. 2005). With the cities of Portland, Vancouver, Longview, and Astoria on its banks, the Columbia River below Bonneville Dam is the most urbanized section of the river.

Sublethal concentrations of contaminants affect the survival of aquatic species by increasing stress, predisposing organisms to disease, delaying development, and disrupting physiological processes, including reproduction. In juvenile salmonids, contaminant exposure can result in decreased immune function and generally reduced fitness (Northwest Power and Conservation Council 2004).

A recent study by Loge et al. in the Columbia River will likely bring more attention to the effects of contaminants on salmonids in the estuary. The study documents infectious disease in outmigrating juvenile salmonids attributed to abiotic stressors, such as chemicals, that influence host susceptibility to infection. The study estimates delayed disease-induced mortalities in chinook salmon related to exposure to contaminants at 1.5 percent and 9 percent for estuary residence times of 30 to 120 days, respectively (Loge et al. 2005). Other contaminants in the water column, including endocrine-disrupting substances such as synthetic hormones, are only beginning to be characterized in the estuary, but these contaminants could have substantial effects on salmon and steelhead (Fresh et al. 2005).

The exposure of stream-type juveniles to contaminants in the plume is understudied. The Lower Columbia River Estuary Partnership currently is leading an effort to develop a model of contaminant flux in the estuary as it relates to juvenile salmonids. The model will identify natural processes and anthropogenic perturbations that affect the estuarine environment. Initial products should be available toward the end of 2006.

Affected salmonids: It is likely that stream-type juvenile salmonids are most affected by short-term exposure to waterborne contaminants such as organophosphate pesticides and dissolved metals (Fresh et al. 2005). Ocean-type juveniles are affected by short-term exposure, too, but they also experience mortality from bioaccumulative toxicants such as DDT and PCBs that are absorbed during longer estuarine residence times (Fresh et al. 2005).

Limiting Factor: Bioaccumulation Toxicity. Potentially toxic water-soluble contaminants, trace metals, and chlorinated compounds have been observed in the estuary (Fresh et al. 2005). DDT and PCBs have been detected at elevated levels in juvenile salmonids using the estuary. These substances concentrate in animals near the top of the food chain. In a 2005 study by Loge et al., delayed disease-induced, contaminant-related mortalities were estimated at 1.5 percent and 9 percent for juvenile chinook residing in the Columbia River estuary for 30 to 120 days, respectively (Loge et al. 2005). Figure 3-4 shows mean concentrations of PCBs and DDTS found in juvenile chinook in several locations of the Columbia River estuary and other Northwest estuaries.

Limiting Factor: Short-Term Toxicity. A variety of organochlorines (including aldrin, dieldrin, trichlorobenzene, and PAHs) in the estuary are above state and federal guidance levels (Northwest Power and Conservation Council 2004). As mentioned above, sublethal concentrations of contaminants can affect the survival of aquatic species by increasing stress, predisposing organisms to disease, delaying development, and disrupting physiological processes (Northwest Power and Conservation Council 2004). Figure 3-5 shows mean concentrations of PAHs in juvenile fall chinook in various locations of the Columbia River estuary and other Northwest estuaries.

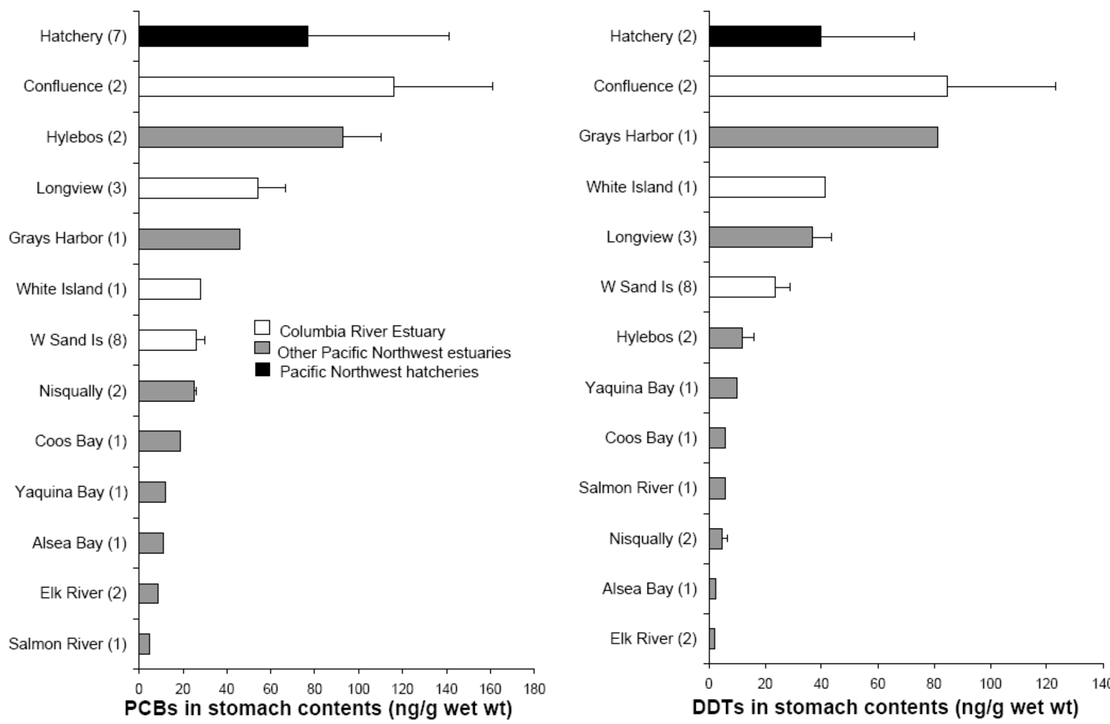

FIGURE 3-4
Mean Concentrations of PCBs and DDTs in Juvenile Chinook
(Reprinted from Fresh et al. 2005.)

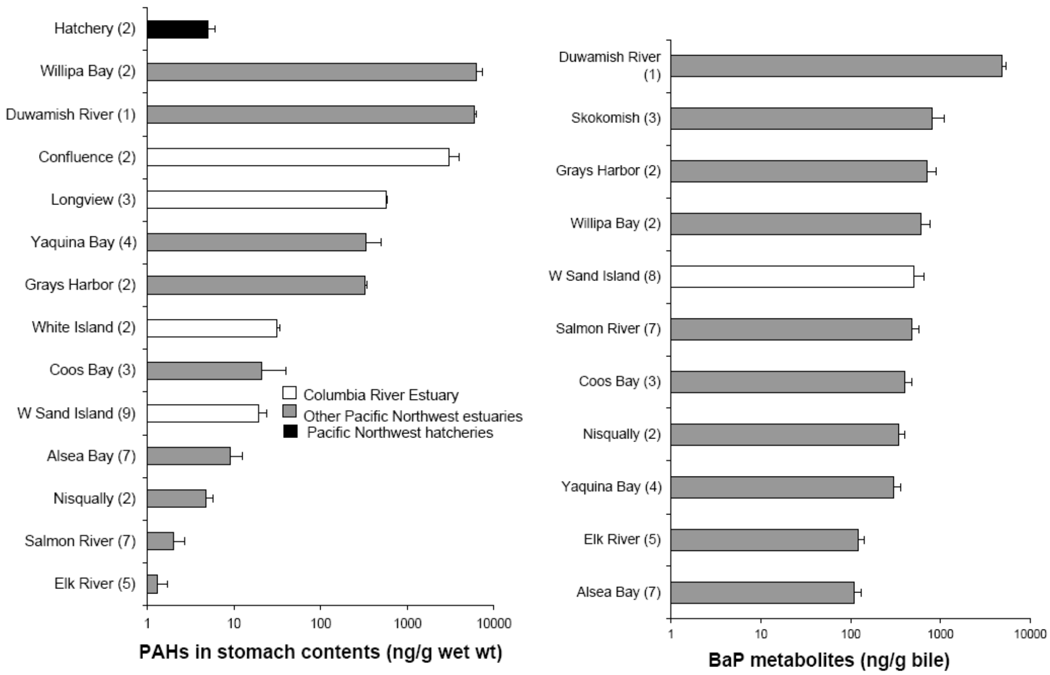

FIGURE 3-5
Mean Concentrations of Polycyclic Aromatic Hydrocarbons (PAHs) in Juvenile Chinook
(Reprinted from Fresh et al. 2005.)

Prioritization of Limiting Factors

All three of the primary literature sources used in this estuary recovery module identified flow, sediment, water quality, and food web alterations as limiting factors. In *Salmon at River's End* (Bottom et al. 2005), each of the limiting factor categories is analyzed in the context of habitat opportunity and capacity and how the limiting factor fits within the member/vagrant conceptual framework. In the Fresh technical memorandum, selected limiting factors are evaluated for their impacts on ocean- and stream-type ESUs. Limiting factors selected for analysis in Fresh et al. (2005) are tern predation, toxics, habitat, and flow. Finally, the "Mainstem Lower Columbia River and Columbia River Estuary Subbasin Plan" and its supplement (Northwest Power and Conservation Council 2004) evaluate limiting factors for their impacts to salmonids and the level of certainty that the factor is limiting.

This estuary recovery module uses a rating system to prioritize limiting factors by ocean- and stream-type salmon and steelhead. For each limiting factor, a score of 1 to 5 was assigned to both ocean- and stream-type salmonids. These scores were based on a synthesis of the three primary literature sources plus a host of others. An initial rating was performed by PC Trask & Associates with input from the Lower Columbia River Estuary Partnership, NOAA/NMFS's Northwest Fisheries Science Center, NOAA/NMFS – Northwest Regional Office, and the Lower Columbia Fish Recovery Board. Additional reviews were used to refine scores. Although the three primary documents did not refer to stranding as a limiting factor, input from Washington Department of Fish and Wildlife staff was used to research the issue directly from other primary sources.

Table 3-1 shows the results of the limiting factor rating process. Each limiting factor received two scores—one for ocean-type salmonids and one for stream-type salmonids. One simplifying assumption in scoring is that both ocean- and stream-type salmonids express a diversity of life history strategies within ESUs and their constituent populations. Relative scores between ocean- and stream-type generally reflect the dominant life history stage by providing extra weight to the dominant life history strategy; however less dominant strategies are considered. For example, reduced off-channel habitat is primarily a limiting factor for ocean-type juveniles because the dominant life history strategy is subyearlings that use shallow-water habitats extensively to feed and rear. However, some ocean-type populations and subpopulations also express a yearling strategy as part of the overall genetic makeup of the population. As a result, both ocean- and stream-type salmonids received scores (albeit lower) for other less dominant life history strategies. The far right-hand column of the table is the total score, which adds ocean- and stream-type impact scores into a single composite score. The assumption that within healthy ESUs there is expression of less-dominant life history strategies is central to *Salmon at River's End* (Bottom et al. 2005) and the Fresh technical memorandum.

Table 3-2 organizes limiting factors into groups based on total score. Top-priority limiting factors are those that have the greatest impact on both ocean- and stream-type ESUs, while lowest priority limiting factors have the least combined impact to ocean- and stream-type ESUs. An important assumption in the rating system is that all limiting factors had an effect on one or both ESU types.

Summary

The identification of limiting factors in the Columbia River estuary is well supported in a variety of literature sources. Although sources take different approaches to lumping limiting factors together or splitting them apart for the purposes of evaluation, all of the documents generally agree that channel confinement and alterations to flows and sediment have significantly degraded the estuary ecosystem in far-reaching ways. Water quality and food web limiting factors also are well documented.

The interconnectedness of these limiting factors suggests the use of ecosystem-based analysis to understand more exactly their effects on salmonids; however, at this point modeling efforts cannot fully explain the complex relationships among limiting factors.

The next chapter examines human actions and natural events that cause or contribute to the limiting factors described in Chapter 3.

TABLE 3-1
Impact of Limiting Factors on Ocean- and Stream-Type Salmonids

Limiting Factor	Level of Impact		
	Ocean Type*	Stream Type*	Total Score
Habitat-Related Limiting Factors			
Reduced in-channel habitat opportunity			
Flow-related estuary habitat changes	5	3	8
Sediment/nutrient-related estuary habitat changes	4	3	7
Reduced off-channel habitat opportunity			
Flow-related changes in access to off-channel habitat	5	3	8
Bankfull elevation changes	5	2	7
Reduced plume habitat opportunity			
Flow-related plume changes	3	5	8
Sediment/nutrient-related plume changes	2	3	5
Water temperature	5	3	8
Stranding	3	2	5
Food Web-Related Limiting Factors			
Food Source Changes			
Reduced macrodetrital inputs	5	3	8
Increased microdetrital inputs	3	2	5
Competition and Predation			
Native fish	3	3	6
Native birds	2	5	7
Native pinnipeds	2	5	7
Exotic fish	2	2	4
Introduced invertebrates	2	2	4
Exotic plants	2	2	4
Toxic Contaminants			
Bioaccumulation toxicity	4	2	6
Short-term toxicity	4	3	7

*Significance of limiting factor to life history strategy:
1 = No likely effects.
2 = Minor effects on populations.
3 = Moderate effects on populations.
4 = Significant effects on populations.
5 = Major effects on populations.

TABLE 3-2
Limiting Factor Prioritization

Limiting Factor	Limiting Factor Score[a]	Limiting Factor Priority[b]
Flow-related estuary habitat changes	8	Top
Flow-related changes in access to off-channel habitat	8	
Reduced macrodetrital inputs	8	
Water temperature	8	
Flow-related plume changes	8	
Bankfull elevation changes	7	High
Sediment/nutrient-related estuary habitat changes	7	
Native pinnipeds	7	
Short-term toxicity	7	
Native birds	7	
Bioaccumulation toxicity	6	Medium
Native fish	6	
Increased microdetrital inputs	5	Low
Sediment/nutrient-related plume changes	5	
Stranding	5	
Exotic plants	4	Lowest
Introduced invertebrates	4	
Exotic fish	4	

[a]From Table 3-1.
[b]Limiting factors have been prioritized in groups, rather than individually, to avoid a false sense of precision in this qualitative analysis.